U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

GEOLOGIC MAP OF SLUMP-BLOCK DEPOSITS IN PART OF THE GRAND MESA AREA, DELTA AND MESA COUNTIES, COLORADO

By

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INTRODUCTION

The slump blocks surrounding Grand Mesa appear to have resulted from retrogressive rotational failure, a type of mass movement that occurs when landslides enlarge opposite to their direction of movement by slumping of successive blocks from the mesa edge (fig. 1). Blocks of relatively rigid cap rock have been transported by sliding in the underlying claystone. Individual blocks moved by rotation and translation. Rotation accounts for backward tilting of the blocks (Yeend, 1969) and translation accounts for much of the separation between them.

This area was chosen for mapping because it presents an opportunity to observe many slumps that differ in size and amount of movement but occur in similar materials and in the same area, and they have similar geologic and climatic history. Slump blocks below the rim of Grand Mesa exist in practically all stages of their evolution, from incipient slumps that have moved less than a meter to old, degraded slumps that have moved hundreds of meters from their original positions and have subsequently been weathered and eroded. Despite weathering, erosion, and deposition of thin glacial deposits, many blocks have been preserved well enough to permit study of geometric relationships between neighboring slump blocks. Analyses of these relationships can provide criteria for hazards assessment in areas where the potential for retrogressive rotational failure exists.

This map area covers the Lands End, Mesa Lakes, and Grand Mesa 7-½ minute quadrangles, which include most of the northern part of Grand Mesa (fig. 2), where slump blocks are well exposed and accessible. The geologic map and cross sections show the size, shape, and distribution of slump blocks as reconstructed by interpretation of surface features (observed in the field or from aerial photographs) and contain basic data needed to analyze retrogressive rotational failure. Previously, the distribution of slump blocks at Grand Mesa has been shown only by a small-scale map (Yeend, 1969); geologic maps have not distinguished individual slump blocks from neighboring surficial deposits (Donnell and Yeend, unpub. mapping, 1961-64; Yeend, 1969; Tweto and others, 1978; Ellis and Freeman, 1984; Ellis and others, 1987; Ellis and Gabaldo, 1989).

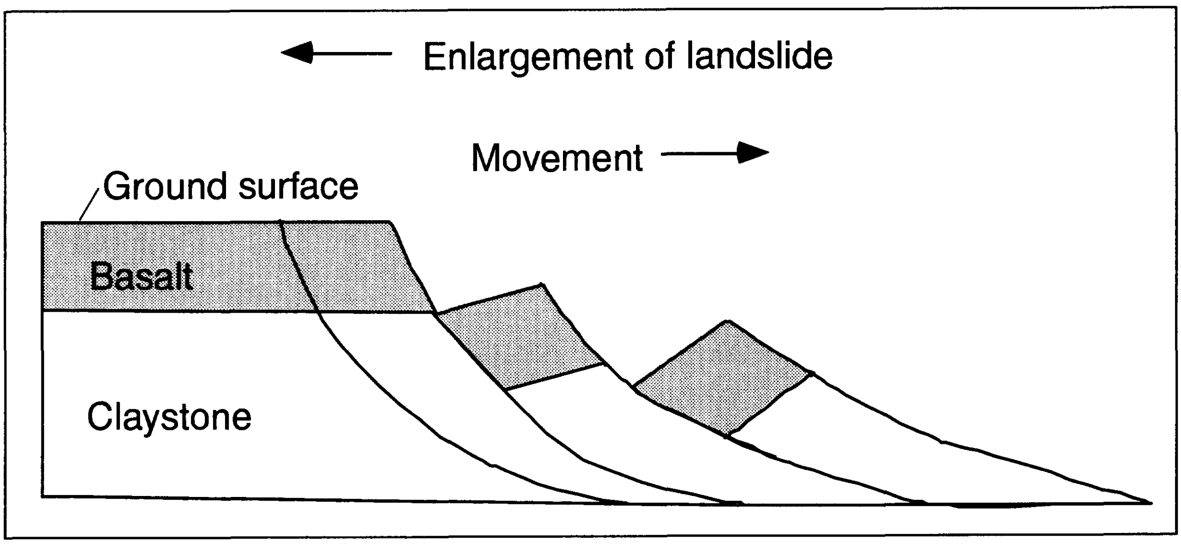

Figure 1. Sketch showing retrogressive rotational failure.

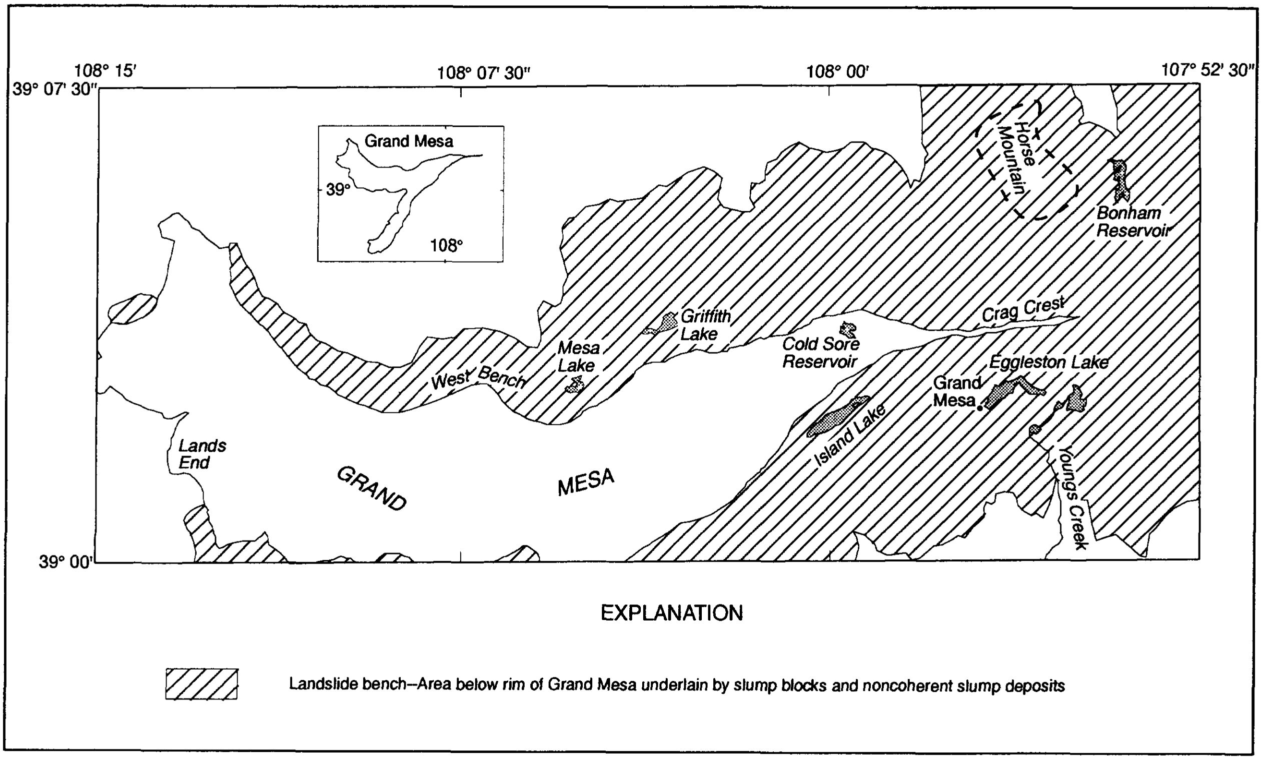

Figure 2. *Locations of geographic features mentioned in text. Hatched area is landslide bench; inset map shows extent of Grand Mesa (map area is north of 39°).*

PREVIOUS WORK

Most previous studies of Grand Mesa have concentrated on bedrock and glacial geology. A.C. Peale described the topography, drainage, and general geology of the area (Hayden, 1876). Henderson (1923), Nygren (1935), and Retzer (1954) reported on various aspects of the glaciation of Grand Mesa, and Nygren (1935) noted the glacial modification of some slump blocks below the rim of Grand Mesa. During the early 1960s, J.R. Donnell of the U.S. Geological Survey mapped the bedrock geology as part of a project to assess oil-shale resources of the Piceance Basin (J.R. Donnell and W.E. Yeend, unpub. mapping, 1961-64). At the same time, W.E. Yeend mapped the surficial (Quaternary) geology of Grand and Battlement Mesas (Yeend, 1969). Since then, several workers have incorporated the mapping of Donnell and Yeend (unpub. mapping, 1961-64) into small-scale maps of the area (Tweto and others, 1978; Ellis and Freeman, 1984; Ellis and others, 1987; and Ellis and Gabaldo, 1989). Yeend (1969, 1973) described slump blocks from Grand Mesa, showed their distribution on a small-scale map, reported on the general causes of the slump blocks, and monitored the movement of several incipient slump blocks. Cole and Sexton (1981) summarized the Quaternary stratigraphy of Grand Mesa.

HOW THE MAP WAS MADE

Map.—We constructed the geologic map by interpretation of aerial photographs (table 1) supplemented by field reconnaissance during 1993 and 1994. The principal purpose of the map is to delin-

Table 1. Aerial photographs used in mapping slump deposits.

[NHAP denotes the National High Altitude Photography program]

Source	Date	Nominal scale	Film type	Roll number	Frame numbers
NHAP _ _ _ _ _ _ _	9/11/83	1:80,000	Black and white.	106	3,4,5
do.	do.	do.	do.	322	14, 15, 16, 50, 51, 52
USDA, Forest Service	9/20/88	1:24,000	Color _ _ _ _ _	988	76, 77, 78, 79, 119, 120
do.	do.	do.	do	1288	156, 157, 158, 159, 199, 200, 201, 202, 210, 211, 212, 213
do.	do.	do.	do.	1388	5, 6, 7, 24, 25, 26, 68, 69, 70

eate boundaries of slump deposits and individual slump blocks beneath the thin veneer of till and other surficial deposits that cover most of the area. We measured all attitudes at outcrops in the field but located contacts between noncoherent slump deposits and coherent slump blocks by stereoscopic viewing of the photographs. A Kern PG-2 stereoscopic plotter was used to transfer fracture traces and the outlines of slump blocks from aerial photographs to the base map. Solid lines on the map indicate the contacts are clear on the photographs (well located by an abrupt break in slope), dashed lines indicate that they are obscure. The downhill limit of incoherent slump deposits, **Qs**, is defined by a distinct break in slope near the top of the Uinta Formation, **Tu**. Remnants of slump deposits downslope from this break in slope are assumed to have become incorporated in earth-flow or other mass wasting deposits included in the unit **Qu**.

Mapping of deposits other than slump blocks was mostly compiled from other sources. Bedrock contacts from J.R. Donnell and W.E. Yeend (unpub. mapping, 1:24,000 scale, 1961-64) have been traced onto the geologic map to show the structure of rocks underlying the area. Between Mesa Lake and Crag Crest, the map also shows traces of shallow dip-slip faults (landslide fractures) that were mapped by Donnell and Yeend (unpub. mapping, 1961-64). We modified the fault traces from their maps where scarps observed on the aerial photographs and in the field indicate that the position of a fault is different than originally mapped. We also added fractures that were visible on aerial photographs but not shown on their maps.

We generalized Yeend's (1969) surficial deposits to simplify the map. Till and other surficial deposits overlying the slump deposits, **Qs** and **Qb**, range in thickness from 0 to 30 m (Yeend, 1969). Yeend's mapping (1969, also unpub. mapping 1961-64) does not distinguish areas where slump deposits crop out within the till, so till and other deposits have been omitted on the landslide bench to show the extent of the slump deposits. On top of Grand Mesa and on slopes below the landslide bench, all surficial units mapped by Yeend (1969) have been combined.

Cross sections.—We constructed cross sections of bedrock in the customary manner by projecting contacts between outcrops. Data from published geologic maps (Ellis and Gabaldo, 1989) established elevations of formation contacts at the south ends of sections C-C′ and D-D′, where nearby outcrops are absent in the map area. We estimated the thickness of basalt, **Tb**, from exposures and from two wells near the west end of Grand

Mesa. In the eastern part of the map area, the height of the mesa rim indicated a minimum thickness for the basalt.

Basal contacts of slump blocks dip roughly parallel to bedding attitudes measured near sections B-B′ and C-C′ and parallel to estimated bedding attitudes for sections A-A′, D-D′, and E-E′. For blocks where no bedding attitude had been measured, dip was assumed to be 0-10° steeper than the back slope of the block, depending on whether the back-slope profile was straight or rounded. Distance from the back slope to the basalt basal contact was less than or equal to the thickness of the basalt cap rock in the section. The position of the curved contact at the back of each slump block was estimated from the position of the scarp for blocks still in contact with the mesa. For blocks that have completely separated from the mesa, the contact is assumed to project downward from the base of the back slope. The curved contact also must be at or above the assumed position of the rupture surface, which is at or above the base of the gravel and claystone unit, **Tgc**. We assumed that the base of noncoherent slump deposits, **Qs**, coincides with a listric fault that dips steeply below the rim of Grand Mesa and joins a rupture surface that slopes a few degrees toward the edge of the landslide bench. The downslope projection of the rupture surface approximately coincides with the top of **Tgc** outcrops near the line of section. Surficial deposits thinner than 15 m are not shown in the cross sections.

STRATIGRAPHY AND STRUCTURE

The map area is in the southern part of the Piceance Basin and within the northeast part of the Colorado Plateau physiographic province. Upper Cretaceous and lower Tertiary (Paleocene through upper Eocene) sedimentary rocks underlie the lower slopes surrounding Grand Mesa. These rocks dip gently to the northeast in the western half of the map area and gently to the northwest in the eastern half of the map area, defining the north-trending axis of the Montrose syncline (not shown), which passes approximately through the center of the map area (Ellis and Gabaldo, 1989).

An unnamed Miocene or Oligocene (William J. Hail, Jr., oral commun., 1994) unit of gravel and claystone unconformably overlies the older rocks. The unconformity appears to dip gently to the west and the gravel and claystone unit thickens from a wedge edge southeast of Lands End to about 240 m beneath Crag Crest. A thick sequence of Miocene basalt flows caps the mesa. The basalt also thickens to the east but dips gently to the southwest. Slumping of the basalt and underlying claystone has destroyed much of the former basalt cap of Grand Mesa and created a broad bench, called the landslide bench, that surrounds the mesa. The landslide bench is covered by many ridges and small hills, but on average it slopes gently (2°-5°) away from the mesa. Glacial and periglacial deposits of Pinedale(?) and Bull Lake(?) age cover much of the area, including some of the slump blocks (Yeend, 1969). These deposits are 0-3 m thick over much of the area and 3-30 m thick in moraines and between some slump blocks. Earth-flow and soil-creep deposits several meters thick cover many of the lower slopes in the western one-third of the map area (Yeend, 1969).

PHYSICAL PROPERTIES OF THE CLAYSTONE

The abundance of claystone beneath the basalt flows is probably a key factor in the widespread slumping of Grand Mesa (Yeend, 1969). We examined deformed beds of claystone and clayey sand exposed in road cuts a few kilometers west and east of the town of Grand Mesa (fig. 2, see geologic map for sample locations) and tested representative samples in the laboratory. Results indicate that the claystone and clayey sand are uncemented or weakly cemented, contain little or no material coarser than 0.425 mm, and behave plastically when remolded (table 2 and fig. 3). The claystone behaves like clay or silt of high plasticity and the clayey sand behaves like clay or silt of low plasticity (fig. 3). High plasticity of the claystone is consistent with the deformation and folding observed in claystone exposures (Yeend, 1969) and with the low shear strength required to explain the widespread slumping shown on the map.

SLUMP BLOCKS

Age.—Most slump blocks moved probably during the Pleistocene and are presently inactive; however, a few incipient blocks (blocks that have been displaced less than a few meters) may have first moved during the late Holocene. Most blocks probably slumped to their present positions before the last glaciation of Grand Mesa (Pinedale); fresh glacial striations are present on both sides (scarp slope and back slope) of several slump blocks, and undisturbed till of Pinedale age is present in valleys between slump blocks. Had striations occurred only on the back slopes of the blocks (former mesa surface) and the till been absent or disturbed between blocks, the blocks would clearly be postglacial features (Yeend, 1969). A few incipient blocks were active in the 1960's and moved 0.0043-0.015 m/yr; however, monitoring over a period of 8 years (1963-1971) detected no movement in others (Yeend, 1969; 1973). Assuming continuous movement at these rates since their inception, and dividing the

Table 2. Description and Atterberg limits of claystone and clayey sand samples from slump deposits.

[First digit of sample number corresponds to sample locations shown on geologic map. Claystone samples were dispersed using an electric blender, then wet sieved and allowed to air dry to about the liquid limit. Atterberg limits were then determined according to standard procedures (ASTM, 1990)]

Sample number	Description	Material retained on #40 sieve[1]	Liquid limit[2]	Plastic limit[3]
1-1	Brick-red claystone	Quartz sand, muscovite, and biotite.	53	27
1-2	Brown clayey sand	Muscovite and fine quartz sand.	44	25
2-B1	Brick-red claystone	none	57	30
2-B2	Tan clayey sand	Muscovite and fine quartz sand, about 1-2 percent of total sample.	31	24
2-C1	Light-green expansive claystone	none	61	30
2-C2	Maroon claystone	Claystone[4]	61	32
3-1	Gray claystone	none	94	45
4-2	Light-gray-brown clayey sand	Biotite, muscovite, and claystone.[4]	45	29
5-1	Light-greenish-gray claystone	Claystone[4]	65	28

[1] Particles larger than 0.425 mm. Less than 1 percent of total sample, unless noted. Minerals listed in order of abundance.

[2] Water content at liquid limit, 100 times weight of water divided by weight of solids.

[3] Water content at plastic limit, 100 times weight of water divided by weight of solids.

[4] Small flakes or grains that did not disperse.

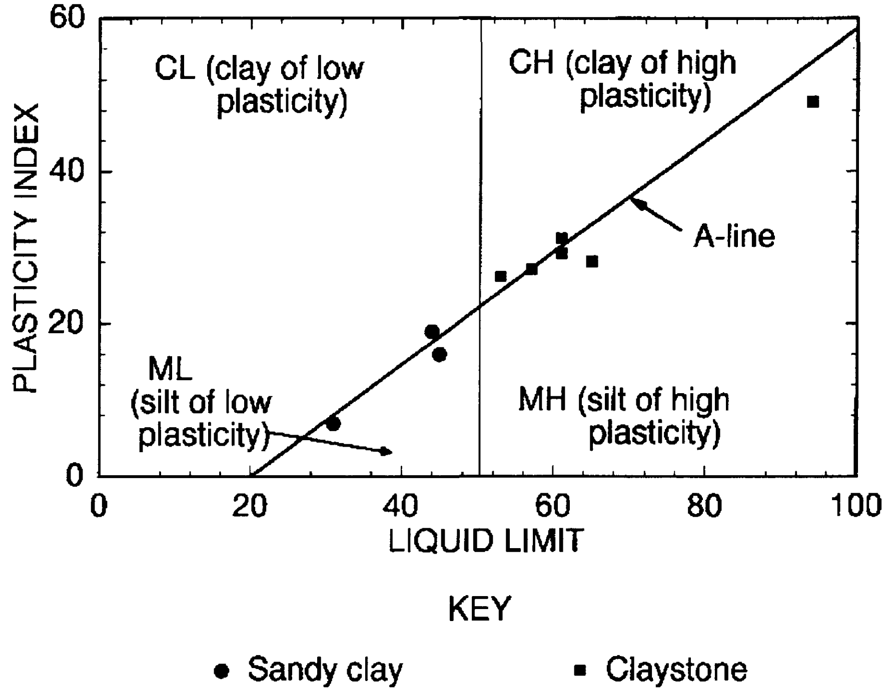

Figure 3. *Plasticity chart for samples of claystone and clayey sand from landslide bench. Plasticity index is difference between liquid limit and plastic limit (table 2). A-line separates soils that behave like clays from those that behave like silts.*

total displacement of the active blocks by their rate of movement, we estimate that some of the active blocks (Yeend, 1973, his locations 1 and 3) could have started moving as little as 130-1500 years ago. Thus, it seems probable that the actively moving incipient blocks first moved during the Holocene. Inactive incipient blocks may have moved either during Pleistocene or Holocene time.

Geomorphology.—Slump-block profiles change gradually as movement and degradation progress. The western part of the map area has been free of glacial ice since the end of Bull-Lake(?) time and glacial processes have done little to alter or obscure profiles of the slump blocks. Study of the map and cross sections, supplemented by field observation, shows that blocks have similar, though less distinct, profiles in areas glaciated during Pinedale(?) time. Figure 4 shows profiles of blocks after various amounts of movement and weathering. The initial profile of a slump block depends on the topography of the mesa top and the underlying basalt. The mesa top undulates gently and slopes toward the southwest. Some flow units in the basalt are thick and massive and form near-vertical cliffs 20-60 m high at the mesa edge (section B-B′ and south end section A-A′), whereas others ravel as an adjacent slump block subsides leaving the mesa edge rounded at the top and talus covered below (north end, sections A-A′ and C-C′). Thus, some slump blocks start out with a nearly flat top, sharp or slightly rounded edge, and a steep, nearly vertical, face; others start with a nearly flat or undulatory top, a rounded edge, and a sloping, talus-covered face (fig. 4A). As a block rotates, dropping away from the mesa and tilting towards it, the relict mesa surface forms a back slope and the former mesa edge becomes the crest of the slump-block ridge (section C-C′, fig. 4B). The back slope gradually becomes steeper as downward displace-

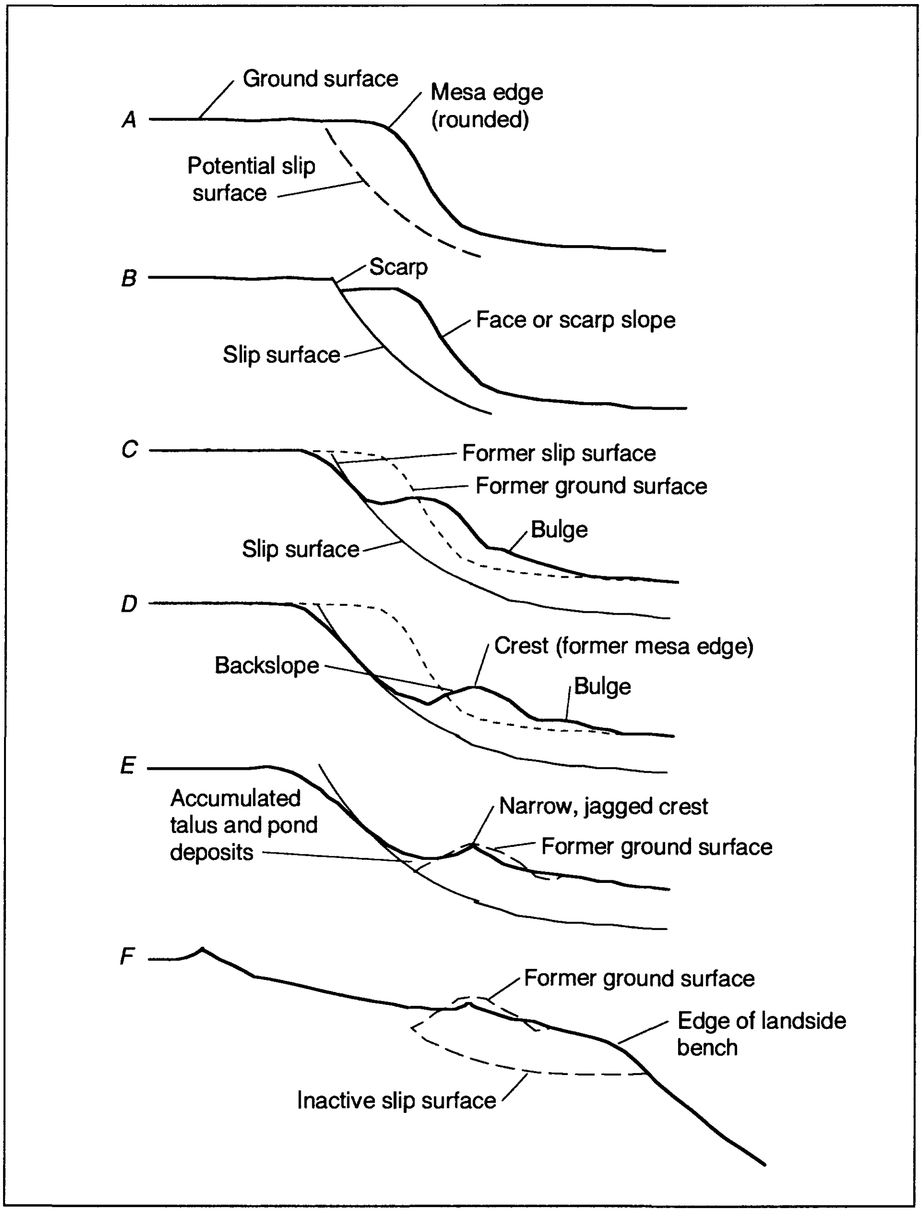

Figure 4. Diagrammatic profiles of a slump block after different amounts of movement and degradation. ***A.*** *Parent cliff.* ***B.*** *Active slump block; downward displacement about ⅛ of cliff height; little degradation.* ***C.*** *Active slump block; downward displacement about half of cliff height; slight rounding of scarp with accumulation of talus deposits at back of block. Former mesa surface and layering of basalt tilted backward, toward mesa. Bulge may begin to form downslope from coherent slump block.* ***D.*** *Active slump block; downward displacement about full cliff height; rounding of scarp with accumulation of talus deposits at back of block; bulging of material downslope from block. Former mesa surface and layering of basalt tilted strongly backward. Bulge downslope from coherent slump block may enlarge.* ***E.*** *Inactive slump block resting on landslide bench (downward displacement about full cliff height); flattening of back slope and scarp slope, development of jagged ridge crest.* ***F.*** *Inactive slump block resting near edge of landslide bench; strongly degraded. Low rounded crest, deeply eroded scarp slope; back slope mostly covered, part of back slope deeply eroded. Downhill part of slump collapsing over edge of landslide bench.*

ment (and backward rotation) increase (fig. 4C). This relation between increasing downward displacement and tilt is apparent in slump blocks south of Mesa Lake, northwest of Island Lake, near Cold Sore Reservoir (section D-D′), and near West Bench. Meanwhile, a linear or crescent-shaped depression forms at the base of the back slope, between the block and the new mesa edge. Ponds or lakes, such as Island Lake (sec. 3, T. 12 S., R. 95 W.), may occupy the depression; most lakes in the area, although retained by artificial dams, occupy such depressions. A low bulge or ridge commonly forms downhill from the coherent slump block (fig. 4C and 4D) probably as a result of compression of claystone and surficial deposits below and ahead of the slump block. Such bulges are apparent downslope from several coherent slump blocks on color aerial photographs of the West Bench area (table 1). Finally, after much downward movement and backward rotation, the block reaches the landslide bench (section D-D′, fig. 4D).

After a block reaches the landslide bench, its slopes begin to flatten; the depression gradually fills with talus deposits and pond sediment until most of the former mesa top is buried (fig. 4E). Meanwhile the crest of the ridge (former edge of the mesa) erodes and ravels to form a narrow, jagged crest ridge and most of the scarp slope below becomes covered with talus deposits (section B-B′). Many blocks near the edge of the landslide bench are soil covered and forested, and have low, rounded, asymmetrical profiles. Such blocks probably represent a late stage of slump-block evolution (fig. 4F). Retreat of steep slopes below the landslide bench undermines blocks near the edge of the bench, resulting in their incremental collapse over the edge of the landslide bench.

Geometry.—Most slump blocks are rectangular, crescentic, or lenticular in plan view; a few have irregular shapes such as the incipient block underlying Cold Sore Reservoir (secs. 27, 33, and 34, T. 11 S., R. 95 W). Regardless of shape, the long dimension is subparallel to the mesa edge. Maximum width is 0.1-0.6 of the length. Strongly crescentic blocks commonly break into three or more main pieces, separated by grabens, when backward tilting becomes great enough to cause the horns of the crescent to point upward. The most obvious examples of broken, initially crescent-shaped blocks are west of Mesa Lake (SE ¼, sec. 34, T. 11 S., R. 96 W.) and on the West Bench (NW ¼, sec. 34, T. 11 S., R. 96 W.).

Layering of the basalt is poorly exposed in most ridges because some flows are thick and massive; thinner flows are strongly jointed and tend to ravel and thereby obscure any layering that might be present. At every place we could observe layering, it typically dips toward the mesa as shown by strike and dip symbols on the West Bench and near Mesa Lake. At some places on the West Bench, the dip direction is strongly oblique to the mesa edge, which is consistent with the observation that some blocks tilt to one side as they move downward (examples at NE ¼, sec. 2, T. 12 S., R. 96 W. and SW ¼, sec. 18, T. 12 S., R. 95 W.). The only place where we found layering dipping away from the mesa is in a small basalt block that had toppled from the mesa edge onto slump blocks below (SE ¼, sec. 31, T. 11 S., R. 96 W.). Dip seems to increase as blocks move downward; layering in blocks still in contact with the mesa generally dips less than layering in blocks that have separated from the mesa. However, attitudes of layering in blocks on the landslide bench show little evidence that dip increases significantly (more than a few degrees) after a block separates from the mesa and reaches the landslide bench. As a result of this general dip toward the mesa, most blocks have asymmetrical profiles; the back slope (former mesa surface) generally slopes less steeply than the scarp slope (former cliff at edge of mesa), which faces away from the mesa (sections A-A′, C-C′, and D-D′).

The main exceptions to this typical profile are in the area east of Youngs Creek (south of Crag Crest) and at Horse Mountain (north of

Crag Crest), where many blocks have flat or rounded tops and subsymmetrical profiles (section E-E'). Structure in these areas is problematical because of the indistinct profiles, lack of data on tilt of layering, and uncertainty about the widths of individual blocks. One interpretation of the structure of Horse Mountain is that it comprises a series of horsts and grabens that have subhorizontal bedding. This interpretation follows from the apparent close spacing of blocks and their rounded tops, which can be expected to reflect the underlying structure as elsewhere, unless the rounding is the result of glacial abrasion. However, it is likely that glacial erosion of ridge crests and deposition of glacial till in low places between blocks (Yeend, 1969) have modified the profiles of the blocks at Horse Mountain and east of Youngs Creek. The obvious tilt of blocks next to Crag Crest, as well as the striking similarity in form between Horse Mountain and the group of tilted slump blocks east of Mesa Lake, indicate that Horse Mountain, like most other areas, is probably underlain by tilted blocks, rather than horsts and grabens.

Distribution.—With few exceptions, slump blocks are widely distributed on the landslide bench. In most areas the blocks are subparallel to the mesa edge, forming straight rows where the cliff is straight and concentric patterns in semicircular reentrants, as along West Bench. Spacing is variable; blocks commonly appear to have from a quarter to several block widths between them. In the area between Horse Mountain and Eggleston Lake, smaller blocks appear to be perched atop larger ones. A similar situation exists, on a smaller scale, in the slump blocks south of Mesa Lake. Near the downslope edges of the landslide bench, slump blocks typically have low relief and are rounded, highly weathered, and heavily wooded, which makes their identification as slump blocks less certain than elsewhere. Blocks are sparse or absent in the areas of smooth, rolling hills north of Griffith Lake and surrounding Bonham Reservoir; these hills are underlain by deformed red claystone.

Block size apparently increases with the thickness of the material involved in the slumping. The size of individual slump blocks increases from west to east, reaching a maximum near Crag Crest, just as the combined thickness of the basalt and underlying gravel and claystone unit increases from west to east (fig. 5). This relation between block size and thickness may prove useful in hazards assessments of areas subject to slumping, because the width of the zone of greatest hazard due to slumping along a cliff or bluff may depend on the thickness of the units susceptible to slumping.

SLUMP BLOCK KINEMATICS

Rotational retrogressive failure, rather than the more commonly reported retrogressive failure of translatory blocks, appears to operate at Grand Mesa. Field observations and analysis of aerial photographs indicate that nearly all blocks have moved by backward rotation combined with or followed by translation. The dip of depositional layering toward the mesa, the increasing tilt with downward displacement of blocks still in contact with the mesa edge, and the widespread asymmetrical profiles of blocks resting on the landslide bench are all consistent with rotational movement. In contrast, interpretation of the structure of Horse Mountain or hills east of Youngs Creek as a series of horsts and grabens would be consistent with translatory-block sliding (fig. 6, also Hansen, 1965; Voight, 1973). It seems unlikely that slump blocks in the same area and geologic setting would form by two different mechanisms (rotational failure and translatory block failure) unless the transition from one mechanism to the other could be caused by gradual lateral changes in the geometry or physical properties of the gravel and claystone unit and the overlying basalt.

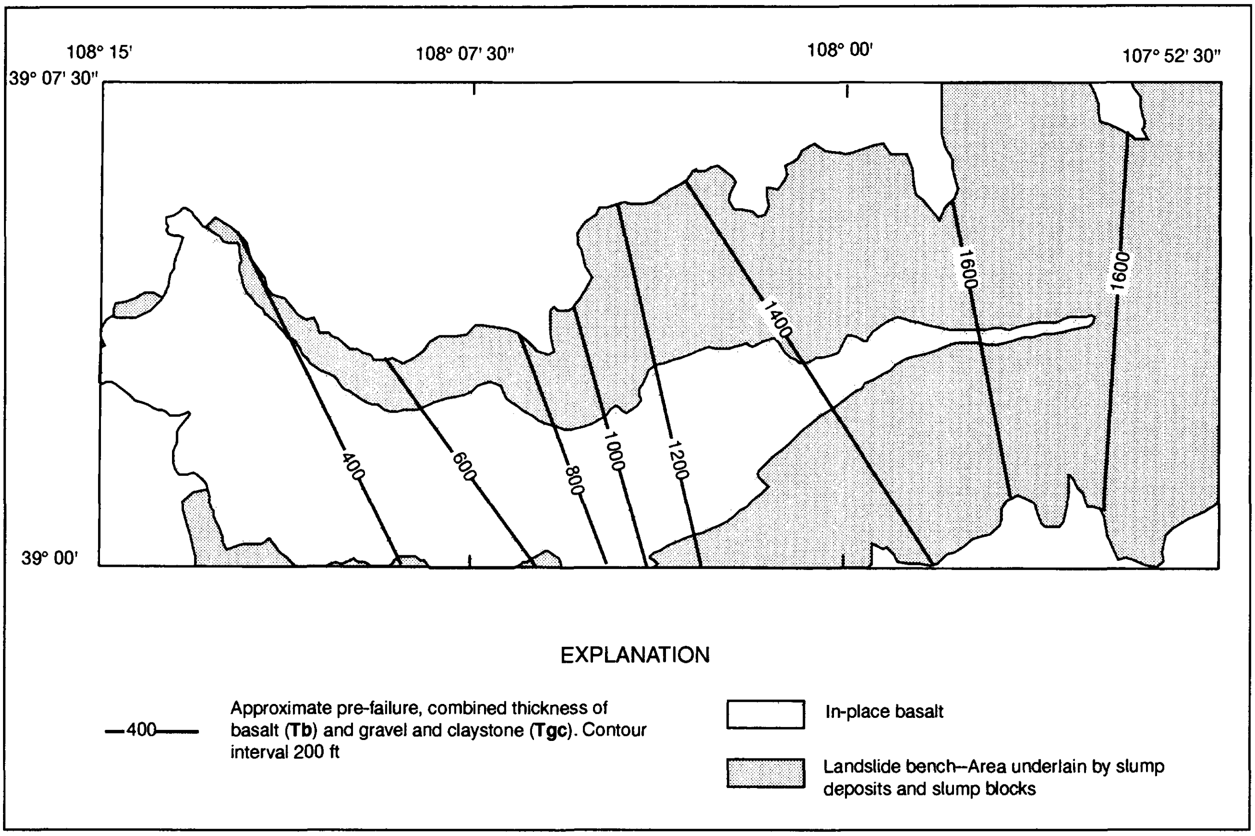

Figure 5. Combined prefailure thickness of basalt flows (Tb) and underlying gravel and claystone unit (Tgc). Thickness estimated from elevation difference between the base of Tgc and projected top of mesa (assumed equal to prefailure top of Tb). In western three-fourths of map area, former elevation at top of mesa determined by projecting lines tangent to index topographic contours on top of mesa to intersect contact between Tgc and Tu.In eastern one fourth of map area (from Crag Crest to the east edge), prefailure elevation at top of Tb assumed to be 11,200 ft.

Rotation alone is insufficient to explain the retrogressive failure that has created the gently sloping landslide bench surrounding Grand Mesa. Once a block has rotated 30°-50°, it typically has undergone large vertical displacement but relatively little horizontal displacement. Rotation apparently ceases because tilt increases little if at all once a block reaches the landslide bench. Outward movement must continue, mainly by translation because the presence of a block at the foot of the slope interferes with rotational movement of the new block failing above and behind it. However, a new, large block can begin to fail before the preceding block has moved more than a few tens of meters downward and forward as depicted in section D-D′ and on the map (sec. 2, T. 12 S., R. 96 W., and secs. 32 and 33, T. 11 S., R. 95 W.). Several kinematic models, such as translation with extrusion, simple shear, bed-normal compression (Muir Wood, 1994), and other models can explain how older, strongly tilted blocks continue to move forward as younger blocks fail and push them from behind. Nearly all these models rely on the movement of slump blocks over a gently dipping rupture surface that extends from the edge of the mesa to the edge of the landslide bench (sections A-A′, B-B′, C-C′, D-D′, and E-E′). Comparisons of the results of such models with the surface and subsurface geometry of slump-block deposits should help determine which models best describe retrogressive rotational failure.

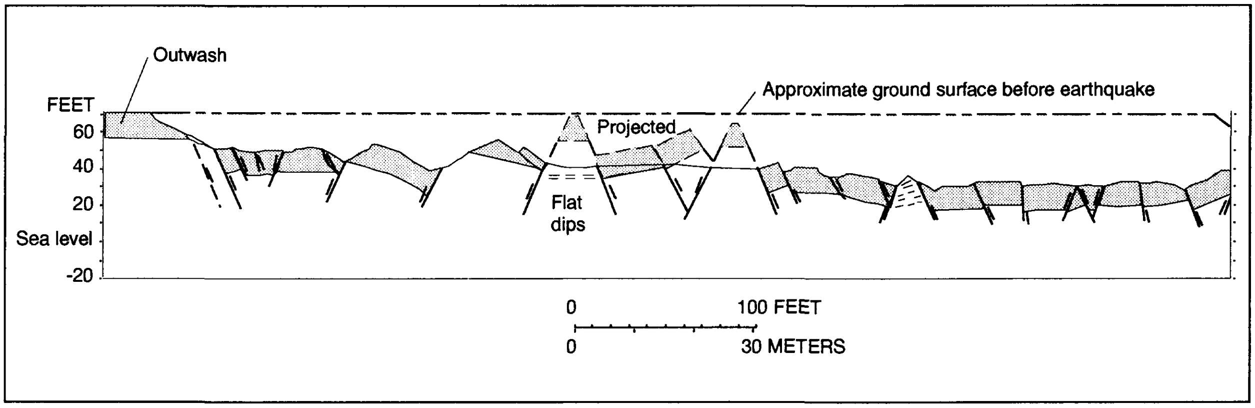

Figure 6. *Cross section of the Turnagain Heights landslide at Anchorage, Alaska, showing typical orientation of retrogressive translatory slide blocks (modified from Hansen, 1965). Horsts form parallel ridges; depositional layering in the horsts is subhorizontal or gently tilted toward parent cliff. Layering in grabens and half grabens typically is subhorizontal, but layering dips moderately either toward or away from parent cliff in some grabens. The ridge spacings and profiles are less regular than those at Grand Mesa.*

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